Strong Gravity, Black Holes & Con-X/XEUS

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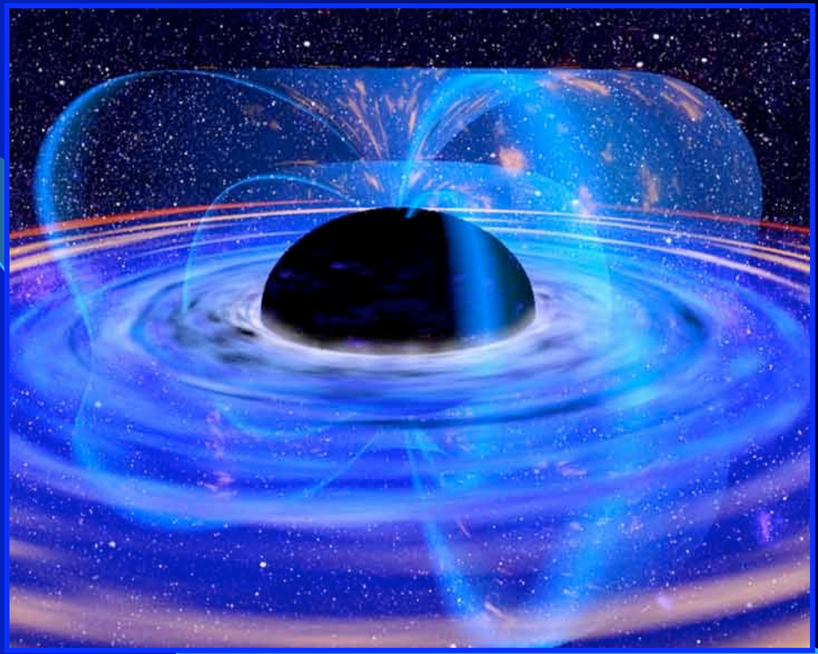


Constellation-X/XEUS meeting
CfA, 23rd February 2005

Strong Gravity, GR…

- Where does GR "break"?
  - All expected failure points are in extreme regimes (Planck scales around a "spacetime singularity"; or on length scale of any compactified extra dimensions)
- We should not <u>expect</u> to find deviations from General Relativity around our black holes
  - Require fundamental modifications to the foundations of the theory to obtain any relevant deviation from GR
  - See the "Six Ways to Axiomatize Einstein's Theory" in MTWs *Gravitation*

… and black hole astrophysics

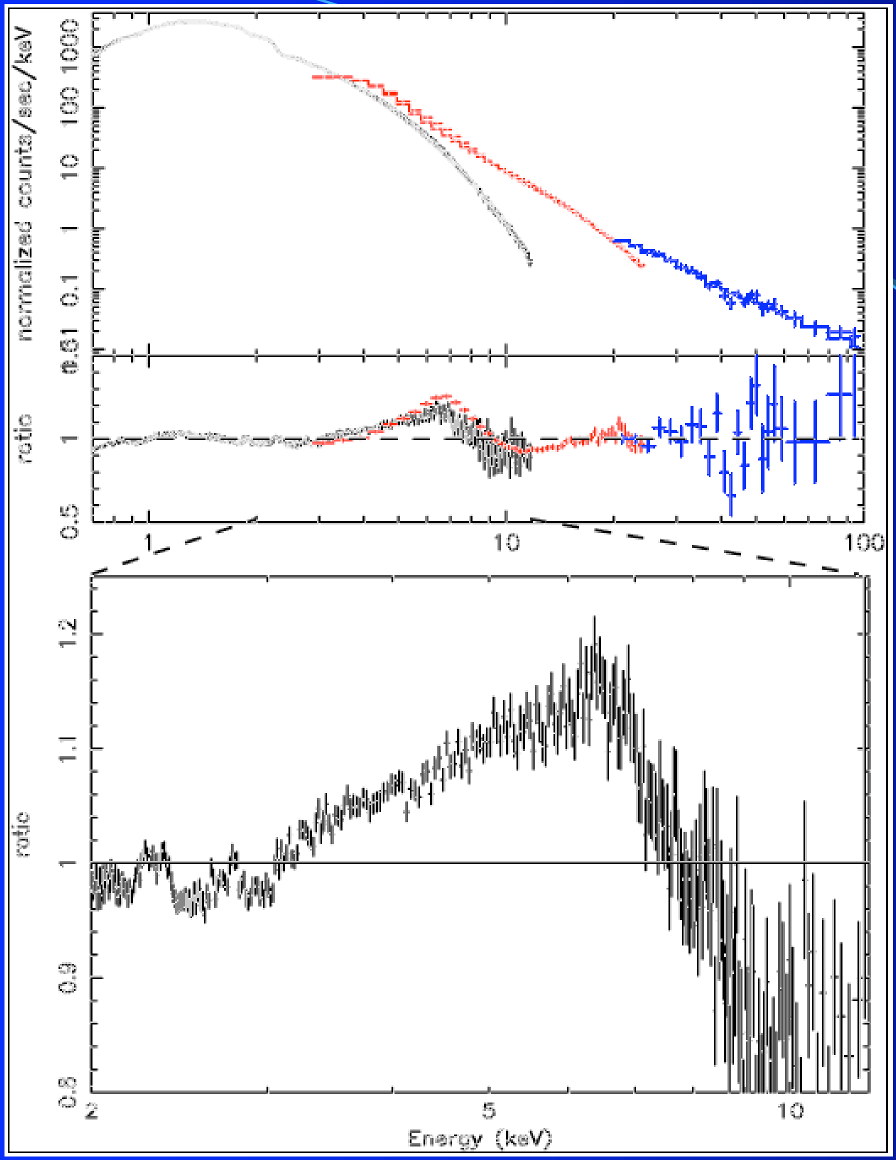
- So, I'll assume GR is correct
- Will focus on observing physics in the strong field background
  - Relativistic dynamics of matter & energy close to BHs
  - Astrophysics of BH spin
  - Physics of the most powerful sources in the Universe
  - Along the way… verify or falsify predictions of GR
- We must let ourselves get excited about this (not apologize for it!)

Probing Strong Gravity with gravitational waves

- As advertised, GWs provide clean, robust, and precise tests of GR
- Merging of supermassive black holes
  - Compare inspiral & ringdown signals with calculations
  - Direct test of "Area Theorem" of GR (few "Golden Binaries" per year; Hughes & Menou 2004)
- Extreme mass ratio inspirals (small BH into SMBH)
  - Can follow 10^5 orbits of the inspiral of "test mass" into a SMBH (albeit over a restricted mass range)
  - Direct test of Kerr metric and the "No-hair Theorem"
  - Expect ~1000 detectable events per year

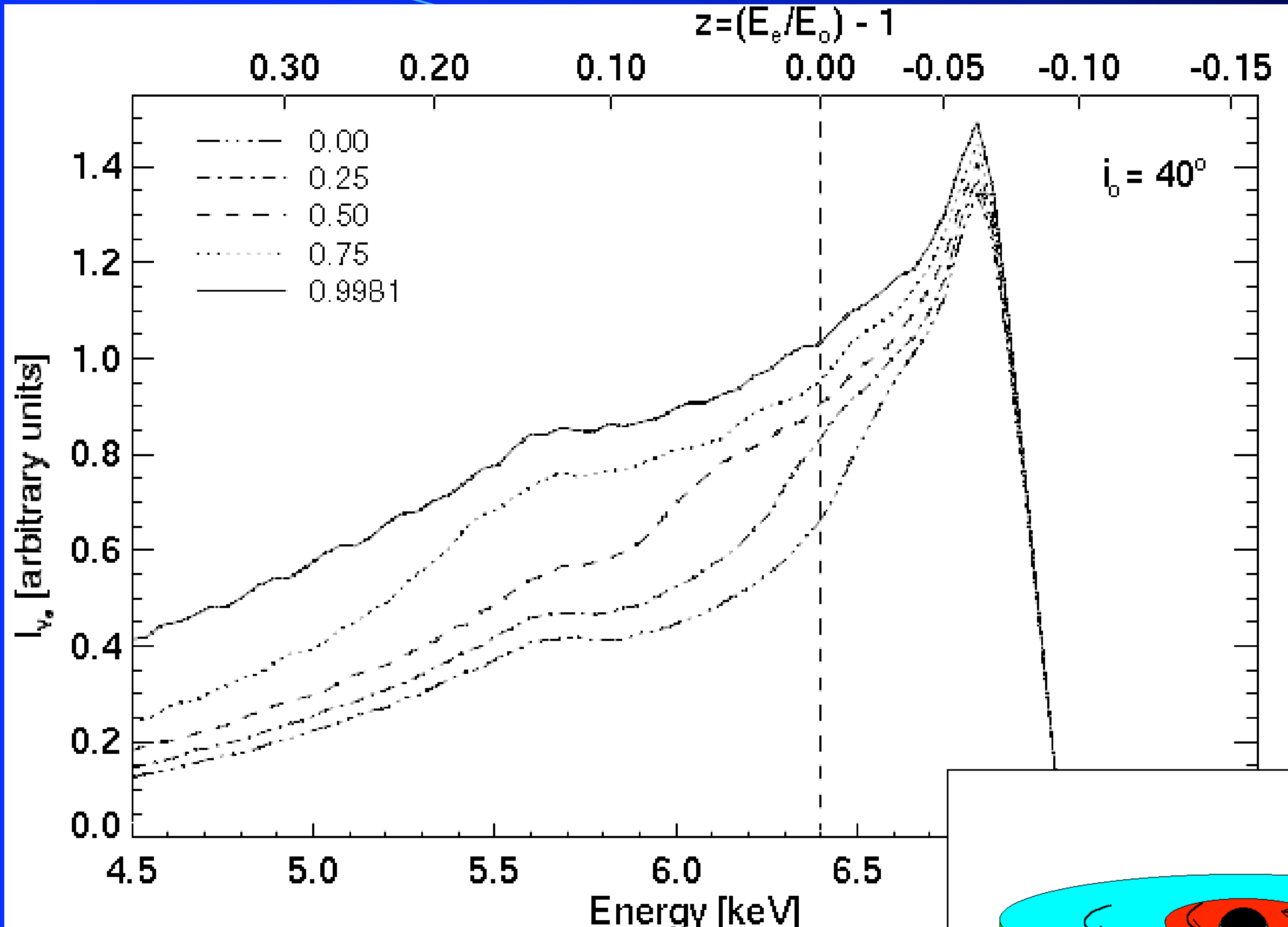
Black Hole Spin

- Astrophysical importance of spin
  - Spin alters structure of inner (energetically dominant) region of accretion disk
  - Spin is potentially a powerful energy source (for disk, jets, other particle acceleration)
  - May well be an important parameter in determining basic nature of many BH-powered astrophysical sources (GBHCs, AGN, GRBs)
- Fundamental physics
  - Observing strong frame-dragging effects $\Rightarrow$ important verification of GR
  - Observing magnetic-extraction of BH spin energy $\Rightarrow$ important verification of GRMHD

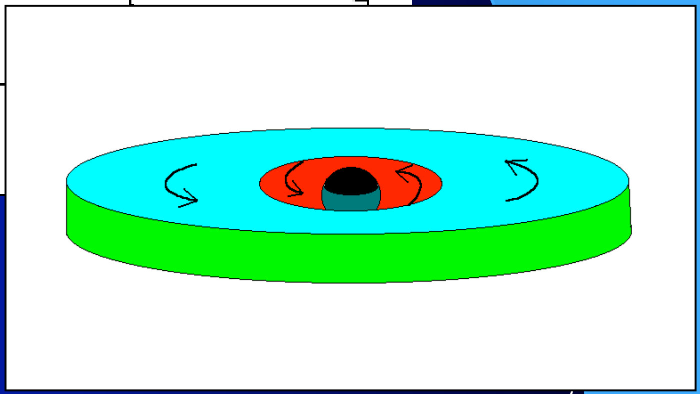


Miller et al. (2004)

GX339-4

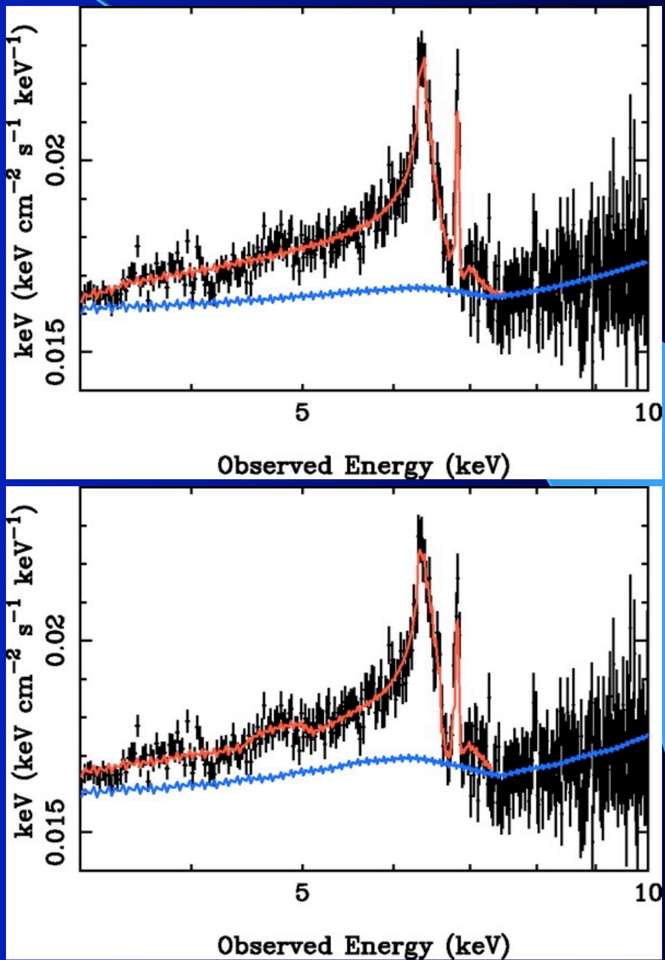


z=(Ee/Eo) - 1
0.30
0.20
0.10
0.00
-0.05
-0.10
-0.15
0.00
0.25
0.50
0.75
0.9981
io = 40°
Iνe [arbitrary units]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4.5
5.0
5.5
6.0
6.5
Energy [keV]



Case study: BH spin in MCG-6-30-15

- Fe line has extreme red-wing… high spin??
- Dovciak et al. (2004) argue that line profile cannot be used to determine BH spin
  - True **only** if one takes no account of whether emission distribution is physically reasonable
- Low spin models need most emission to be deep within the innermost stable circular orbit (CSR & Begelman 1997)



Dovciak, Karas & Yaqoob (2004)

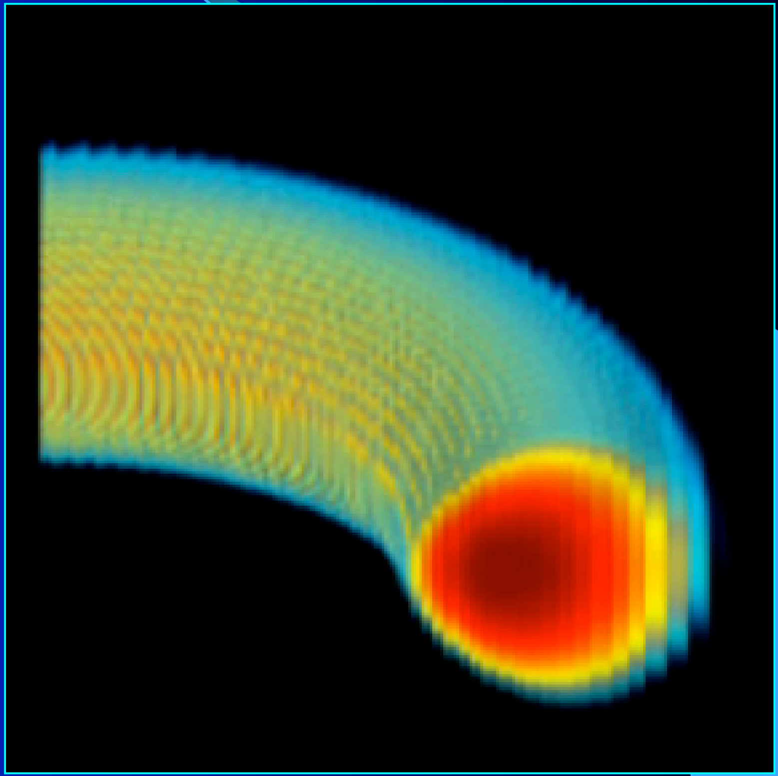
Spin of MCG-6-30-15 (cont)

- **Assume** Schwarzschild hole ⇒ significant line emission from ring at $3r_g$ (i.e., half coordinate radius of ISCO; CSR unpub.)
  - Extremely hard to reconcile with physics of the accretion flow… flow should be fully ionized inside of $4.5\text{-}5r_g$ (due to falling density)
- **Assume** no line emission from within ISCO ⇒ a>0.93 (Brenneman & CSR, in prep.)

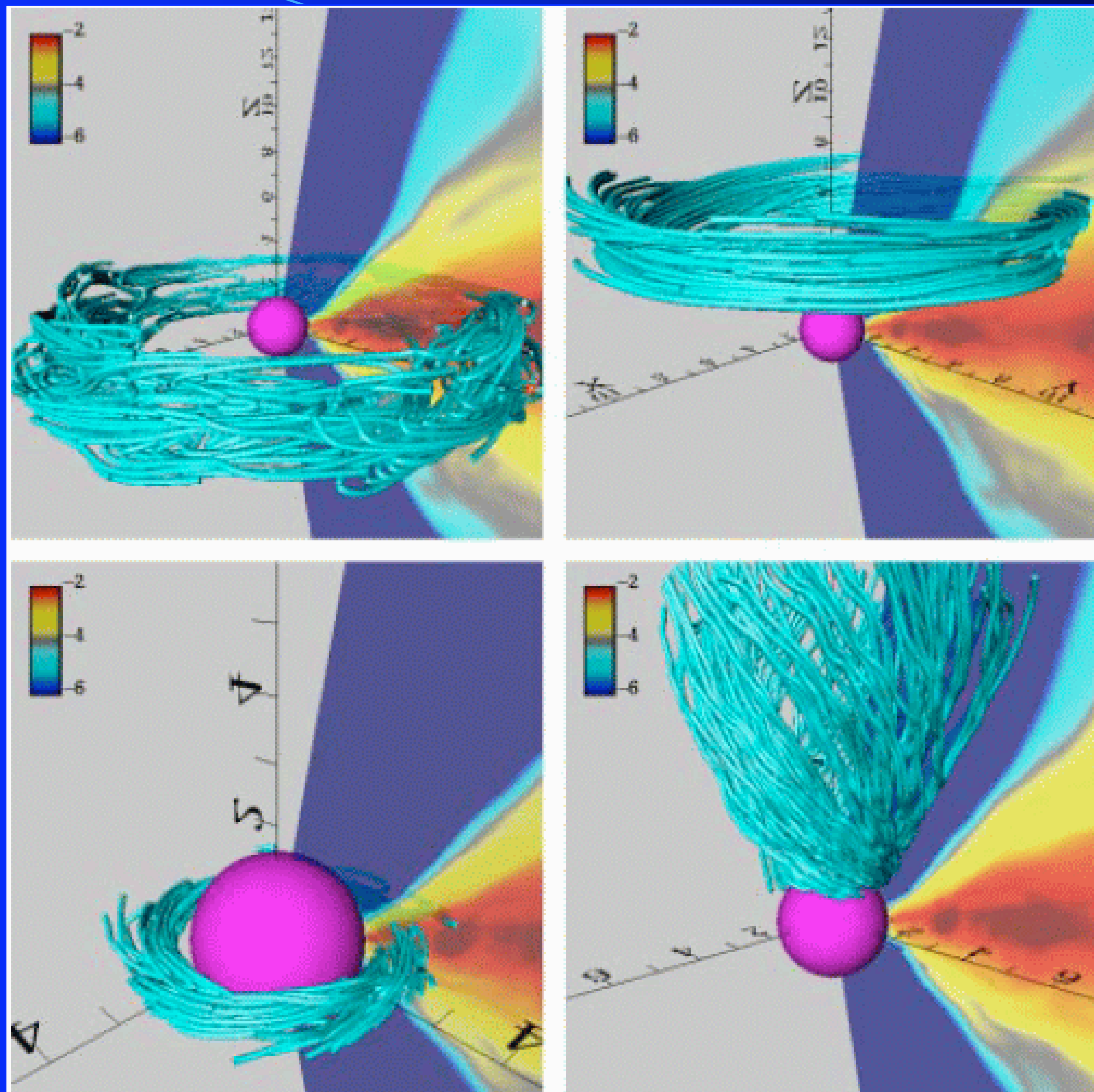
- **Bottom line**: Current data are definitely probing effects related to BH spin, but conclusions depend on accretion disk physics

“Accretion disk physics” isn’t the black box it used to be!

- Rapid development of BH accretion disk theory
  - 1991: Balbus & Hawley realized importance of MRI and MHD turbulence for driving accretion
  - 1995-1996: Local 3D simulations
  - 1998-2000: Global 3D simulations
  - 2002-2003: Global GRMHD simulations

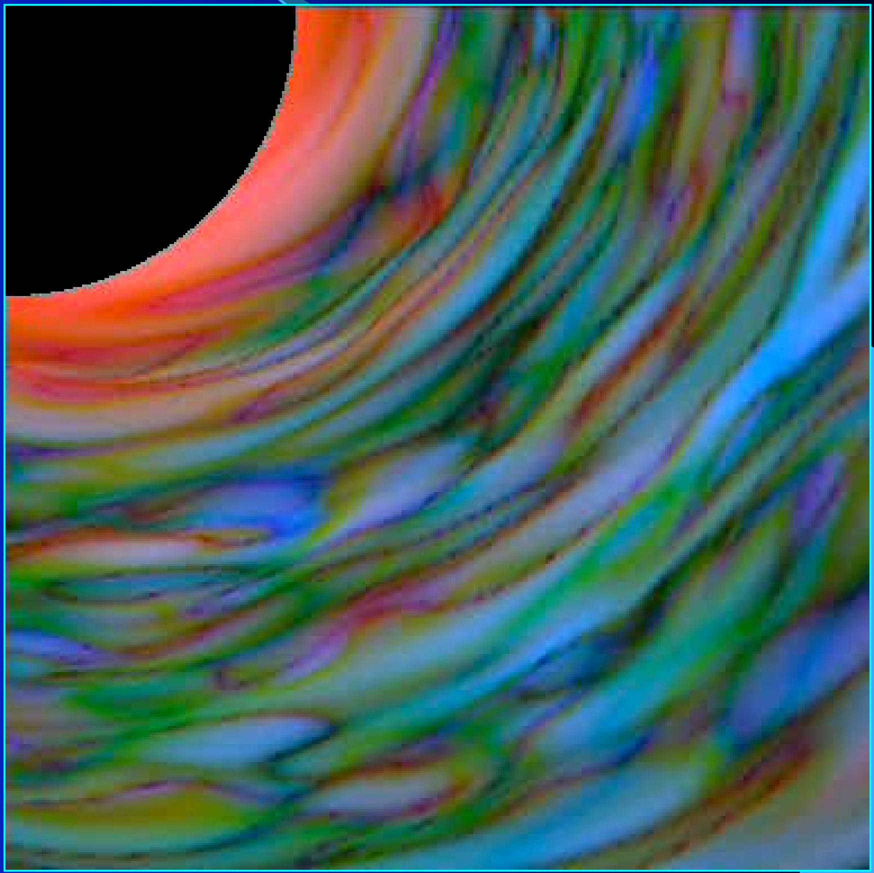


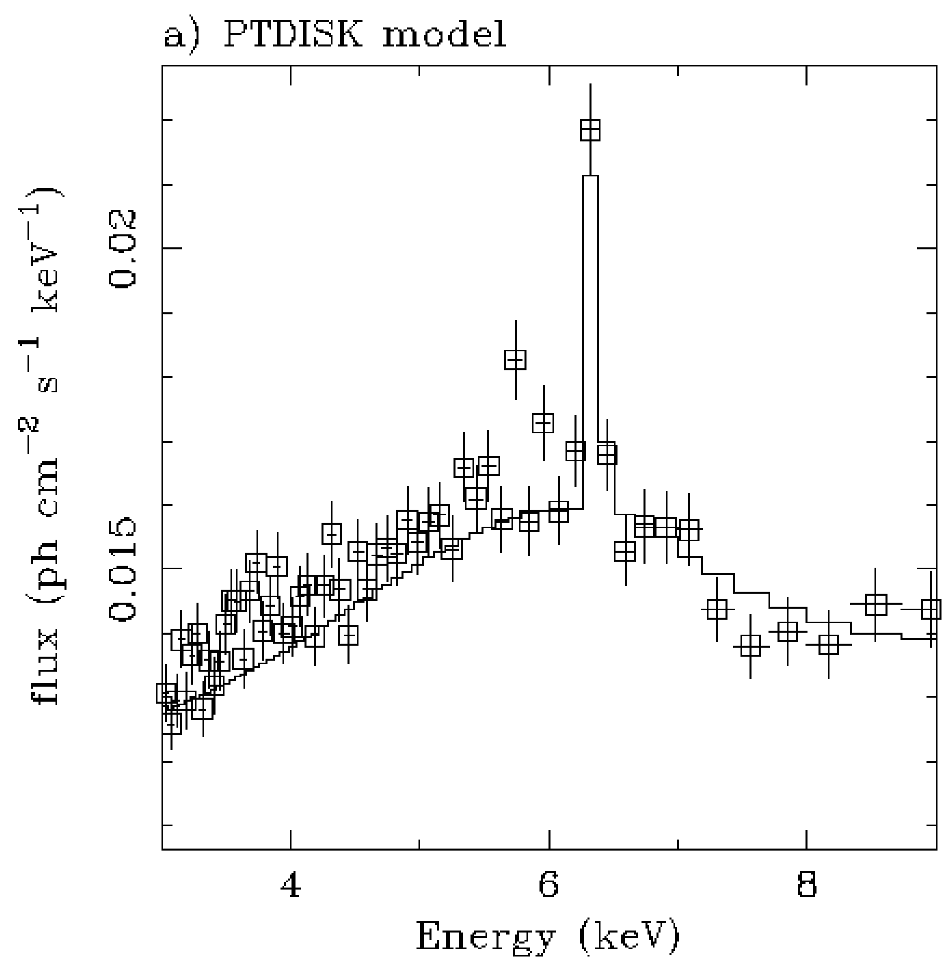
Hawley & Krolik (2000)


-2
-4
-6
-2
-4
-6
-2
-4
-6
-2
-4
-6

Within the ISCO

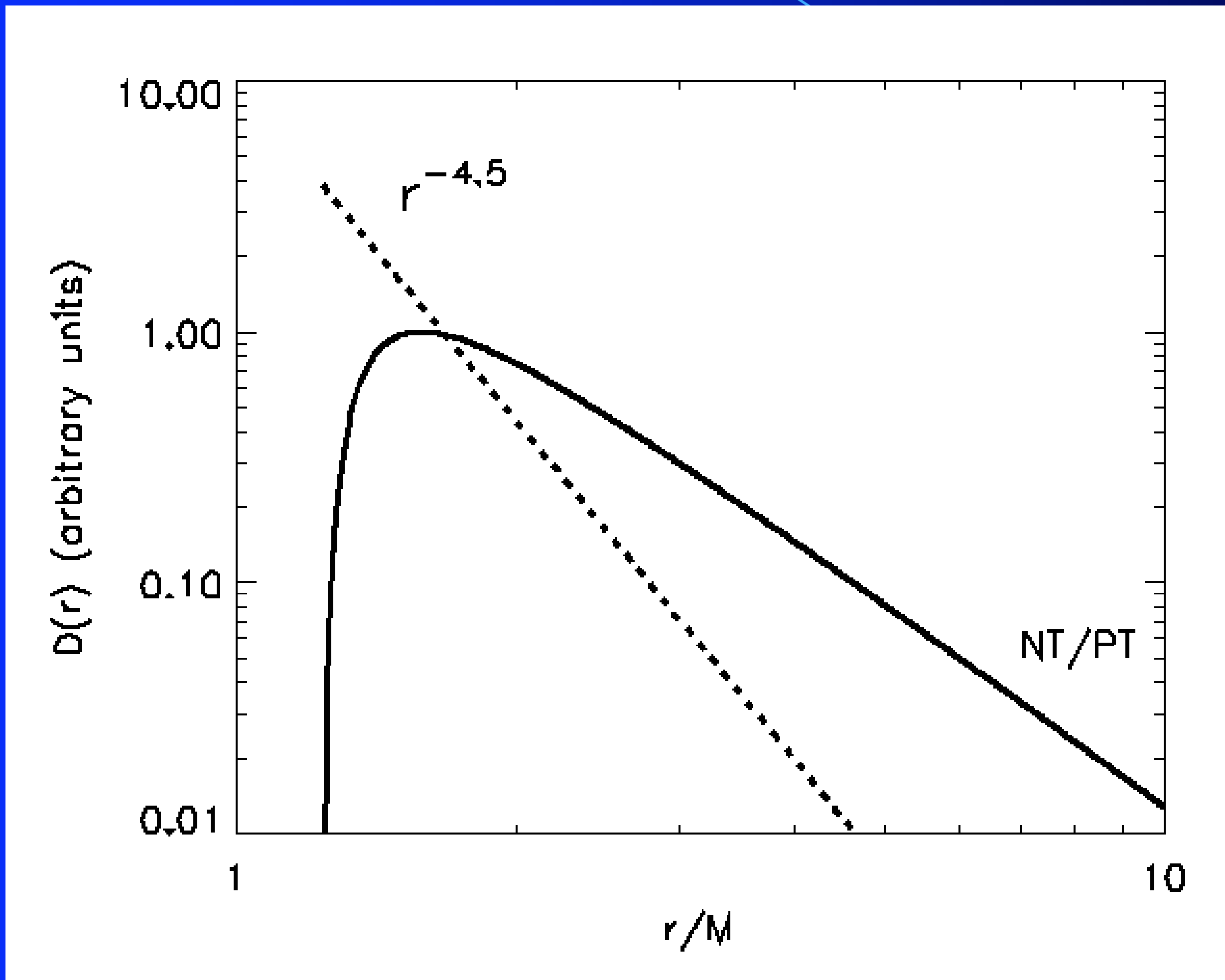
- Excellent prospect for detailed theoretical investigation of region within ISCO in near future
- Have already uncovered some surprises…
  - Material within ISCO may not plunge ballistically…
  - Magnetic connections can lead to energy/ang-mtm extraction as it plunges
- Radiative/ionization properties can soon be examined.



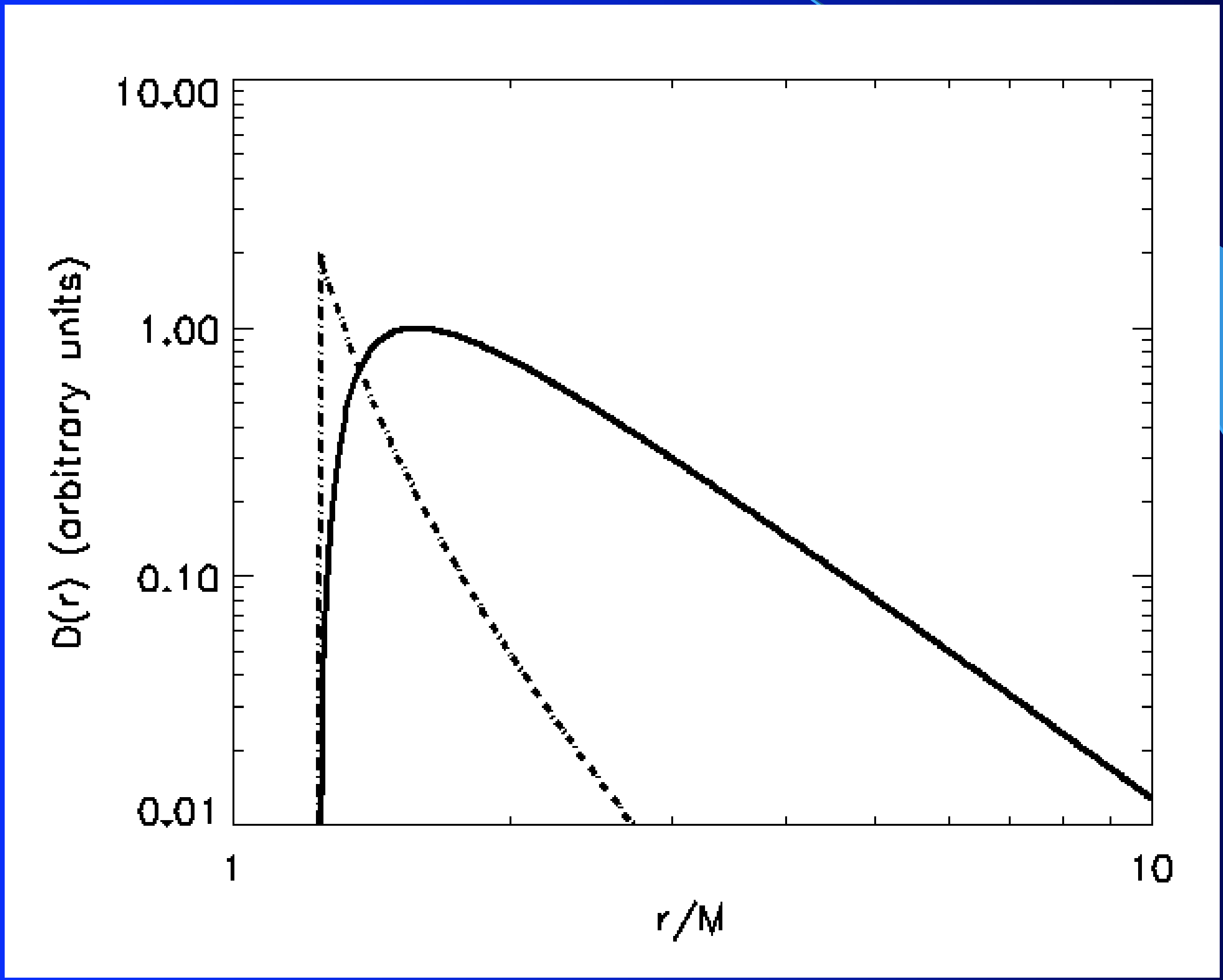


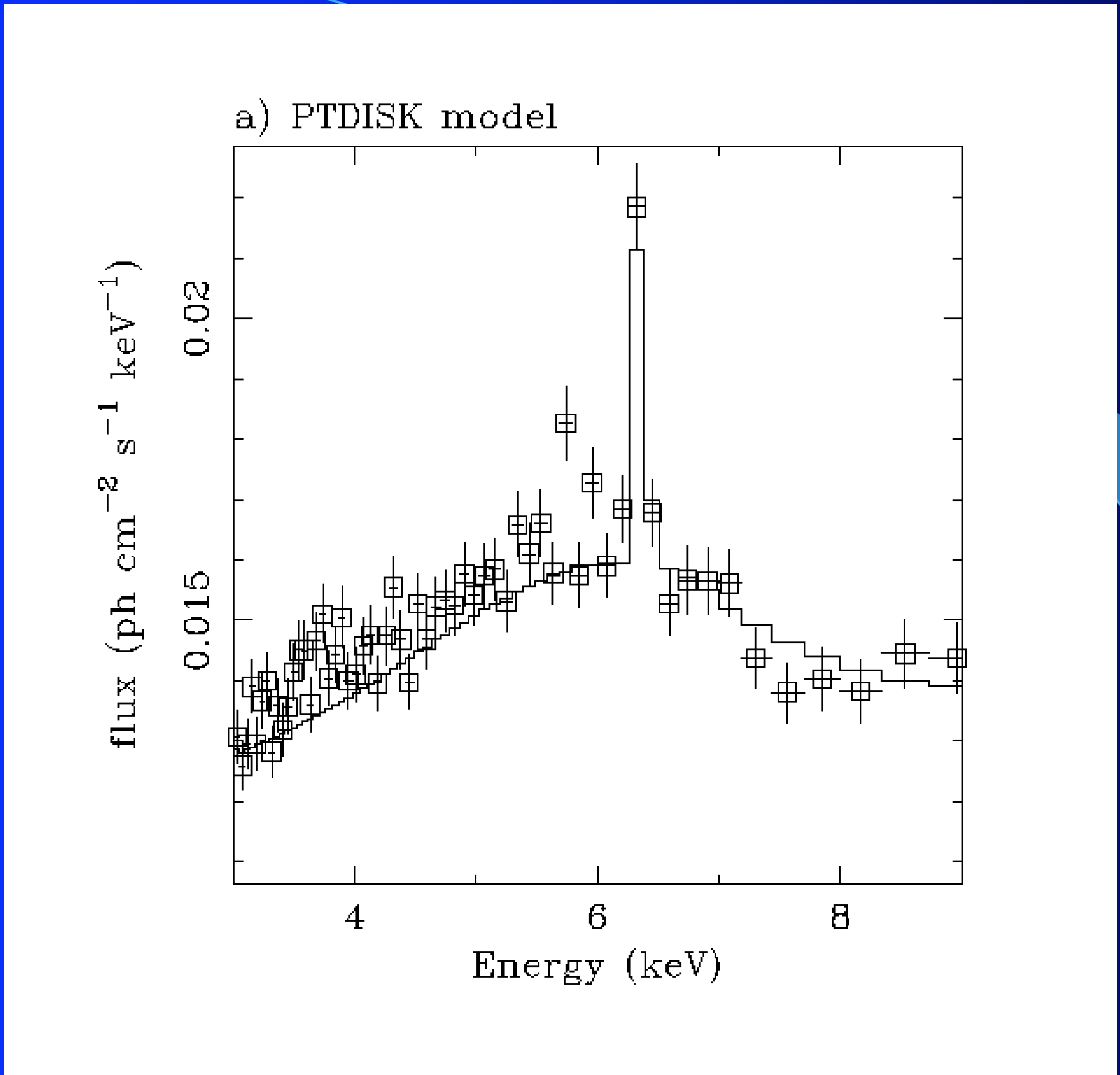
Fit with a Novikov & Thorne disk

Inconsistent with standard disk models of Novikov, Page & Thorne (NPT)…



Additional torquing from the region within the ISCO?





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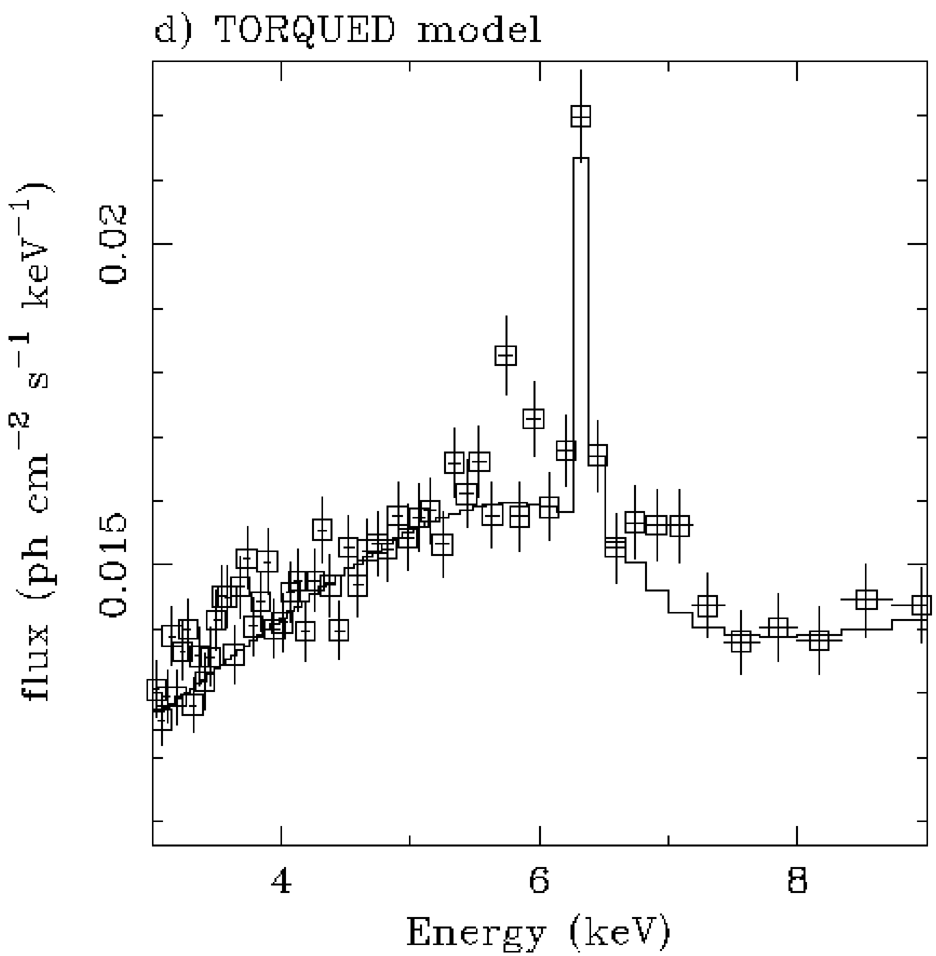

Fit with an Agol & Krolik "infinite-efficiency" disk

Big goals for a next generation X-ray observatory

- I'll focus on spectral work…
- Detailed physics of BH accretion; studies of bright AGN
  - **Rapid spectral variability of X-ray continuum** (physics and geometry of disk, corona and/or jet)
  - **Dynamical timescale iron line variability** (geometry, disk turbulence + orbit of matter around BH)
  - **Light-crossing timescale iron line variability** (geometry + orbit of photons around BH)
  - **Calibration of lower-fidelity diagnostics** (time-averaged line profiles, continuum shapes etc.) for mass, spin and accretion rate
- BHs in the Universe; large samples of objects
  - **Demographics of BH mass, spin and accretion rate** in GBHC, AGN and ULXs from time-averaged iron lines
  - Astrophysics of spin, spin extraction and constraints on BH formation

Specific strategies I : Detailed exploration of disk physics & gravity

- **Special status of bright AGN**
  - **Highest photon flux per light-crossing time**
  - **Best sources to study detailed sub-orbital behaviour**
- Dynamical timescale variability of iron line and continuum radiation
  - Can trace orbits of inhomogeneities in the flow
  - Direct probe of disk turbulence and motion of matter through spacetime
- Relativistic reverberation of X-ray flares from the inner accretion disk
  - Watch X-ray flash echo through system
  - Direct probe of source geometry an motion of photons through spacetime

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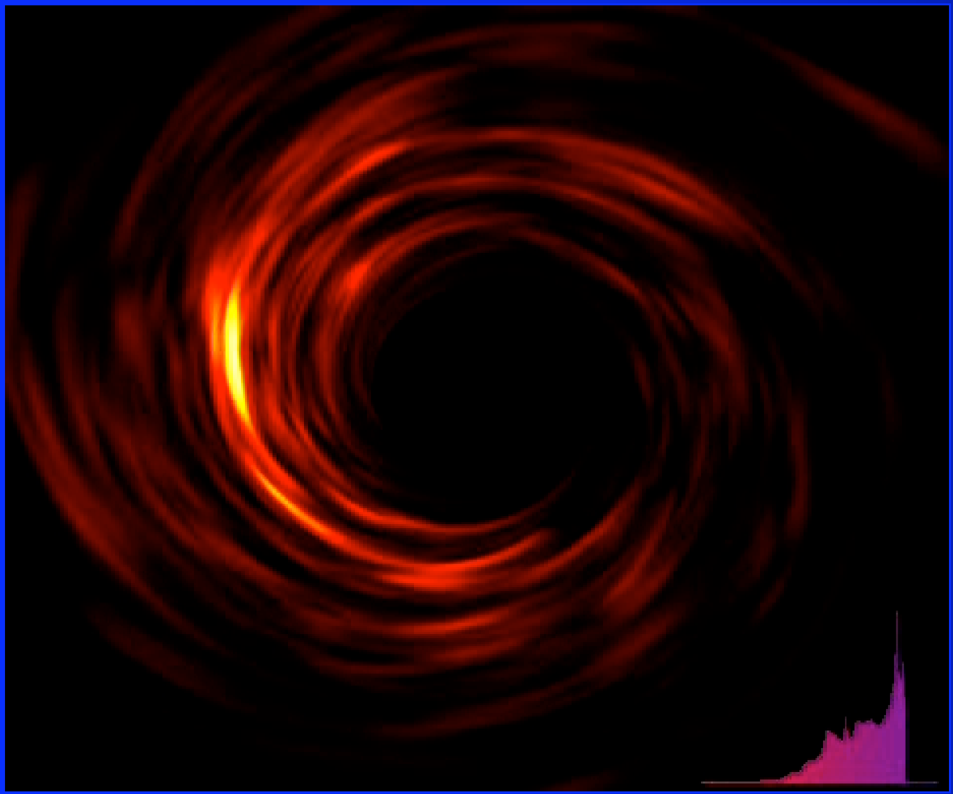
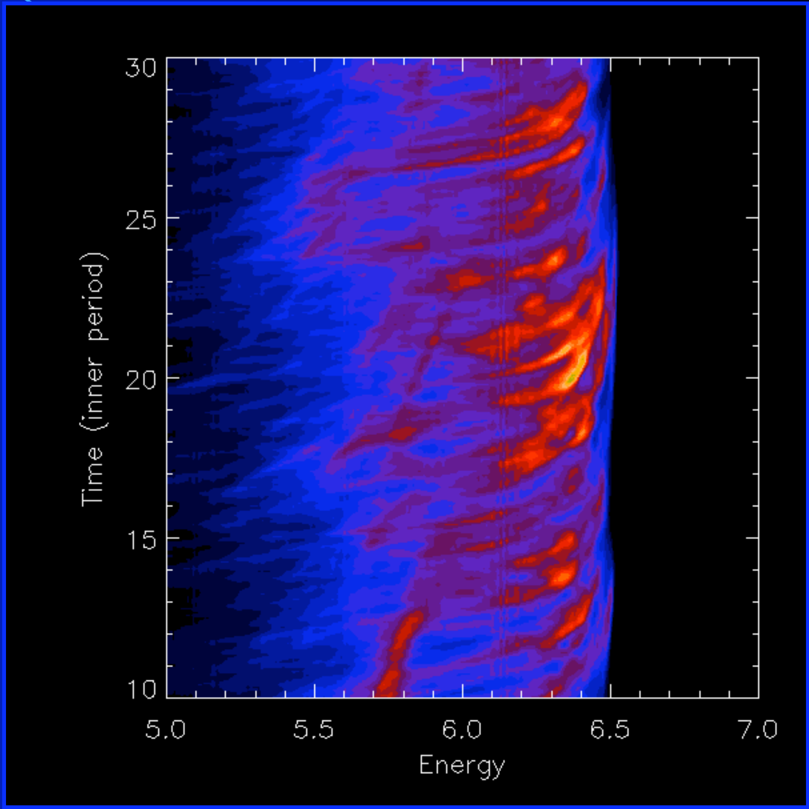
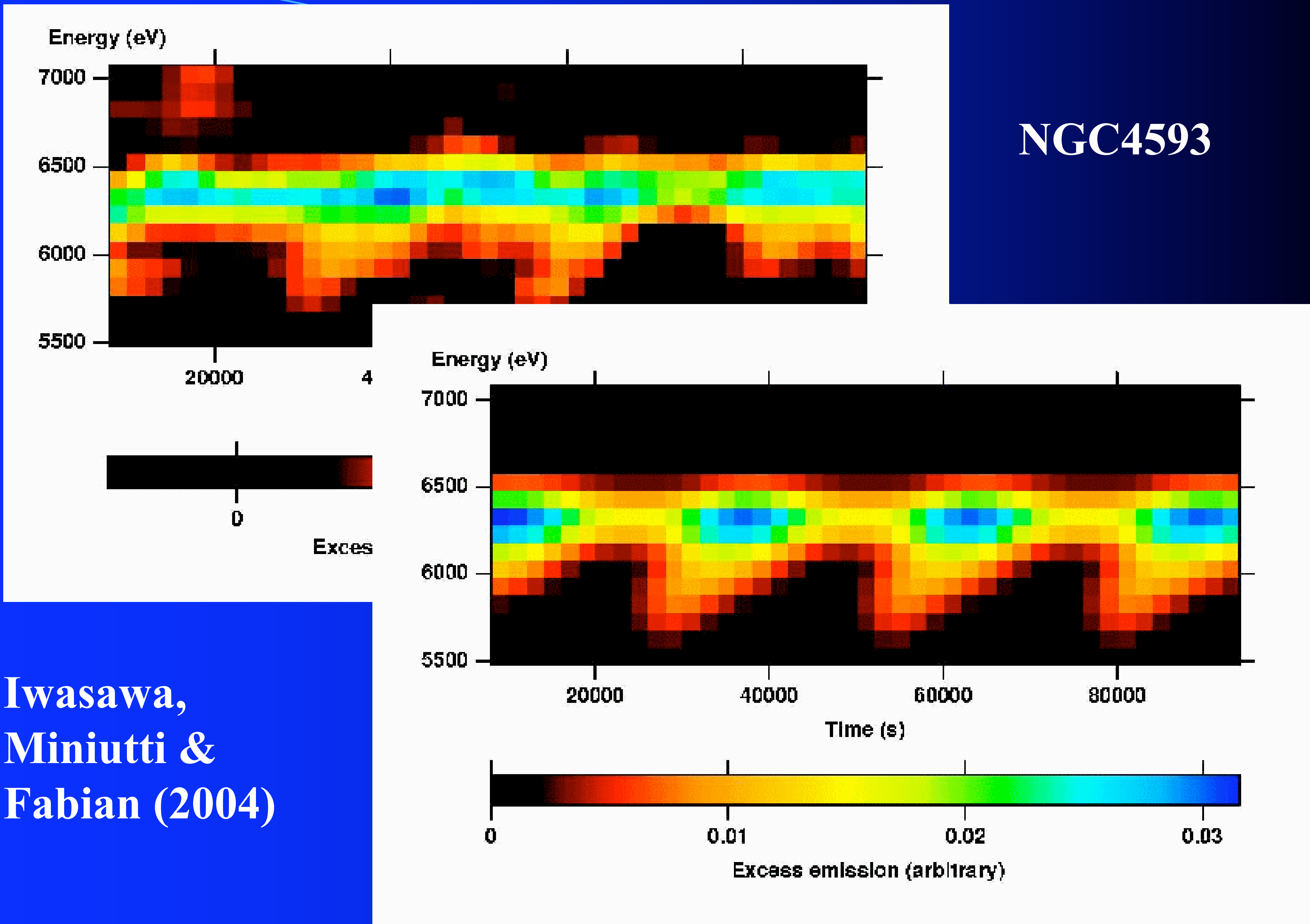




Armitage & CSR (2003)

NGC4593

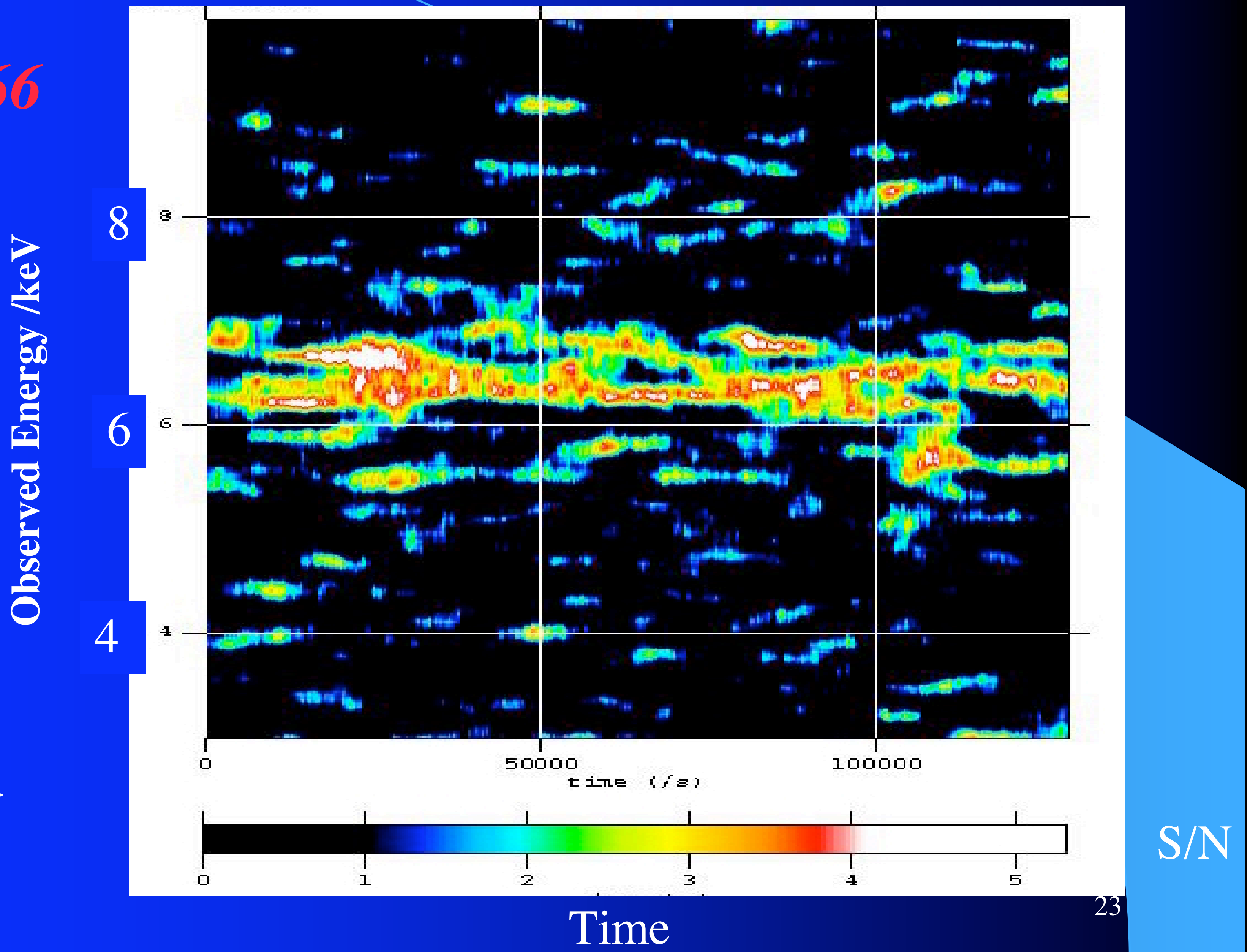


Iwasawa, Miniutti & Fabian (2004)

Courtesy of Jane Turner

Mkn 766

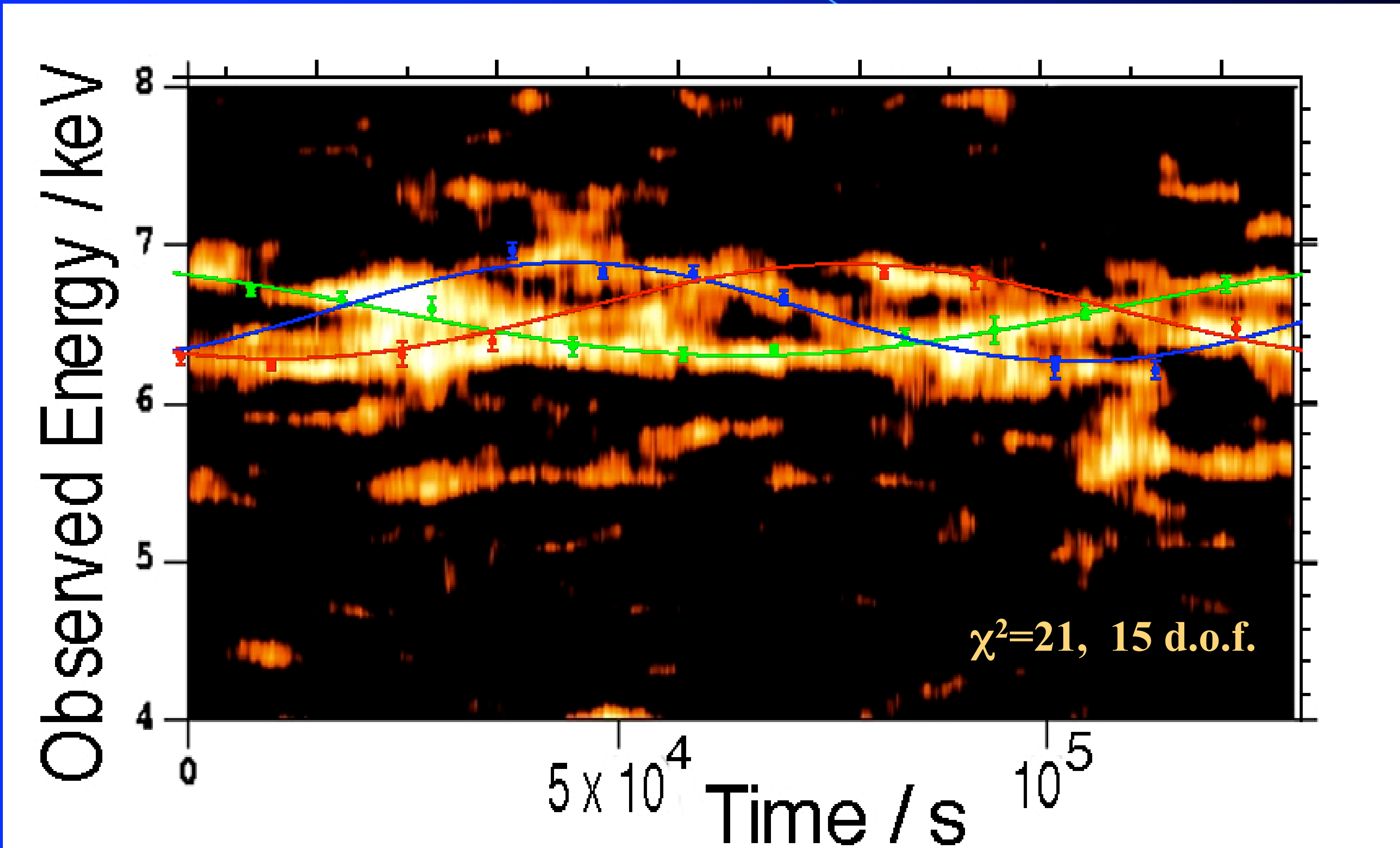
z=0.012



t~100 ks

amplitude > 1 keV

Can fit line maxima by three Keplerian orbits with *same* inclination & central mass !!



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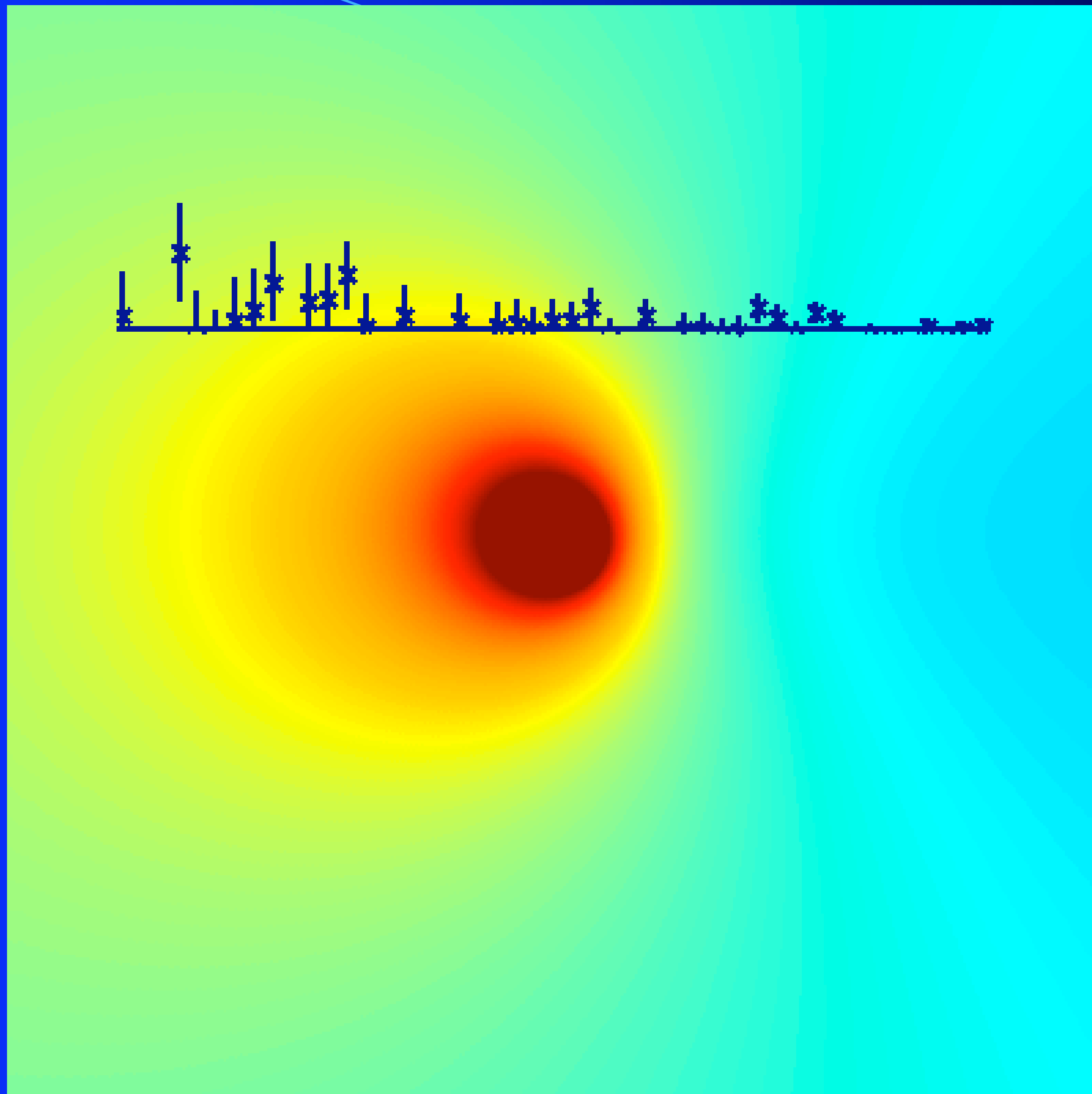

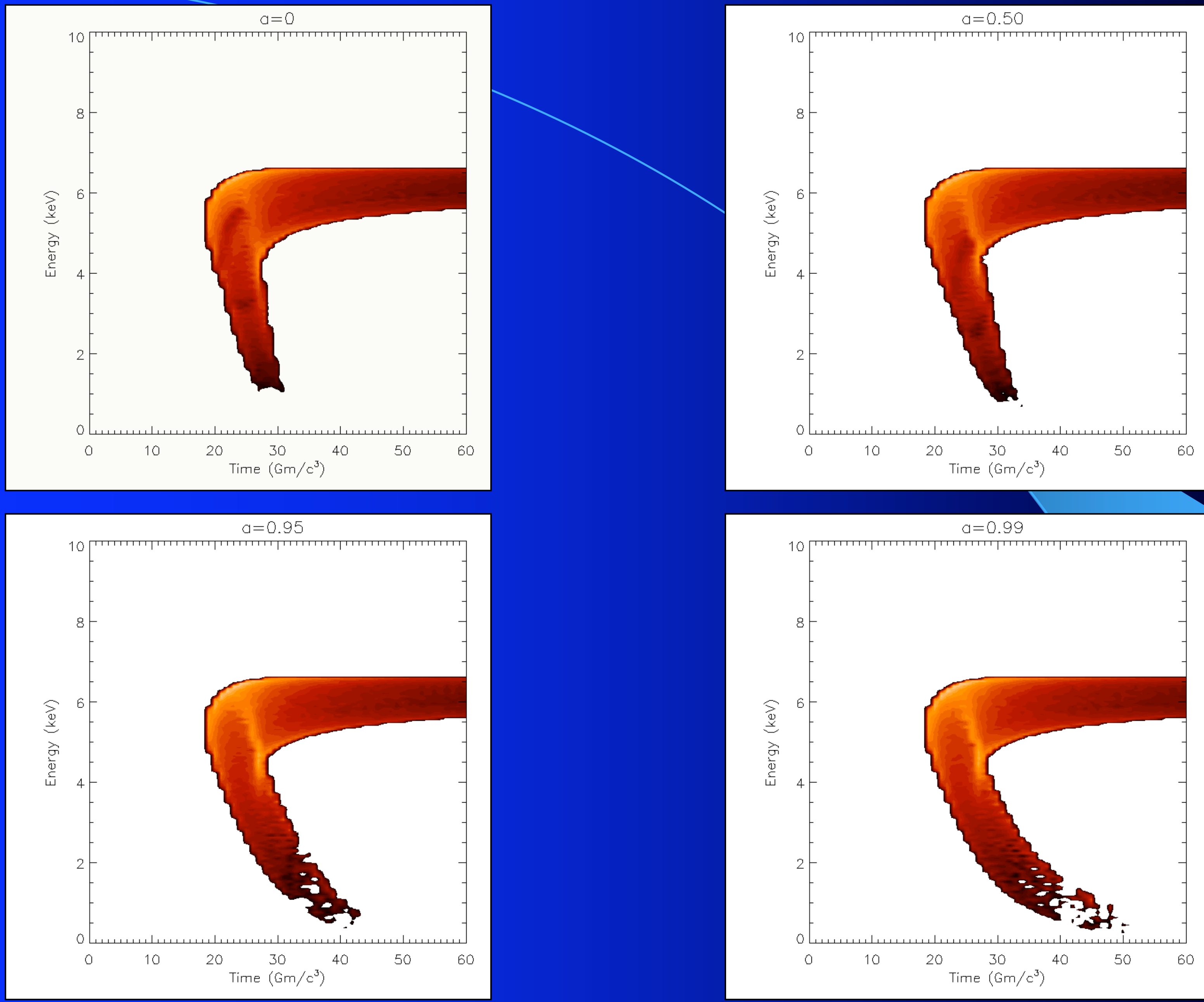

Reynolds et al. (1999)

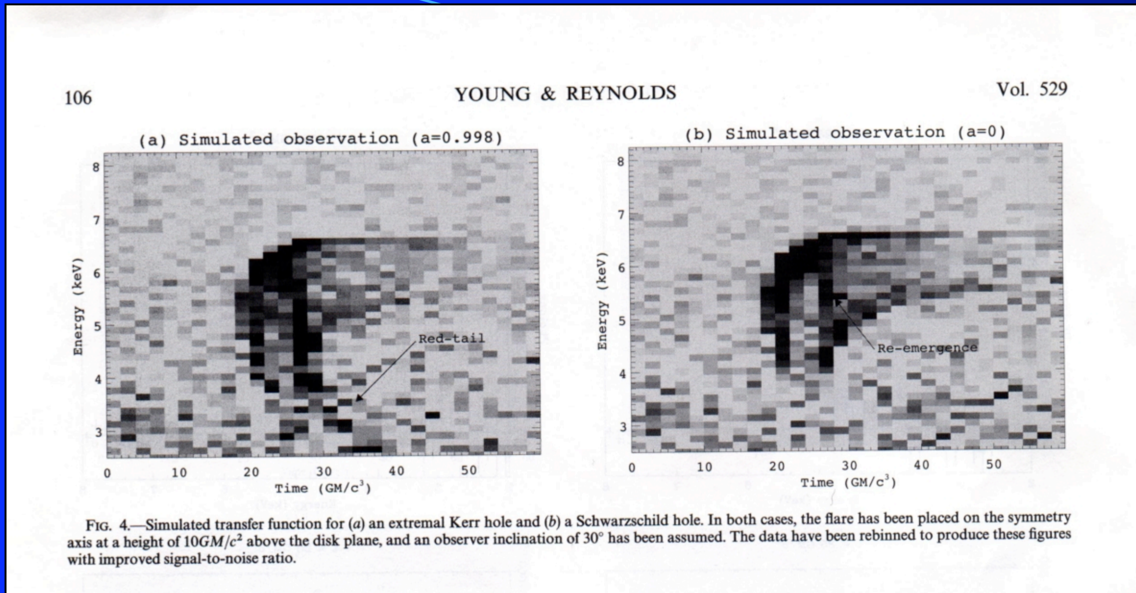

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FIG. 4.—Simulated transfer function for (*a*) an extremal Kerr hole and (*b*) a Schwarzschild hole. In both cases, the flare has been placed on the symmetry axis at a height of $10GM/c^2$ above the disk plane, and an observer inclination of 30° has been assumed. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

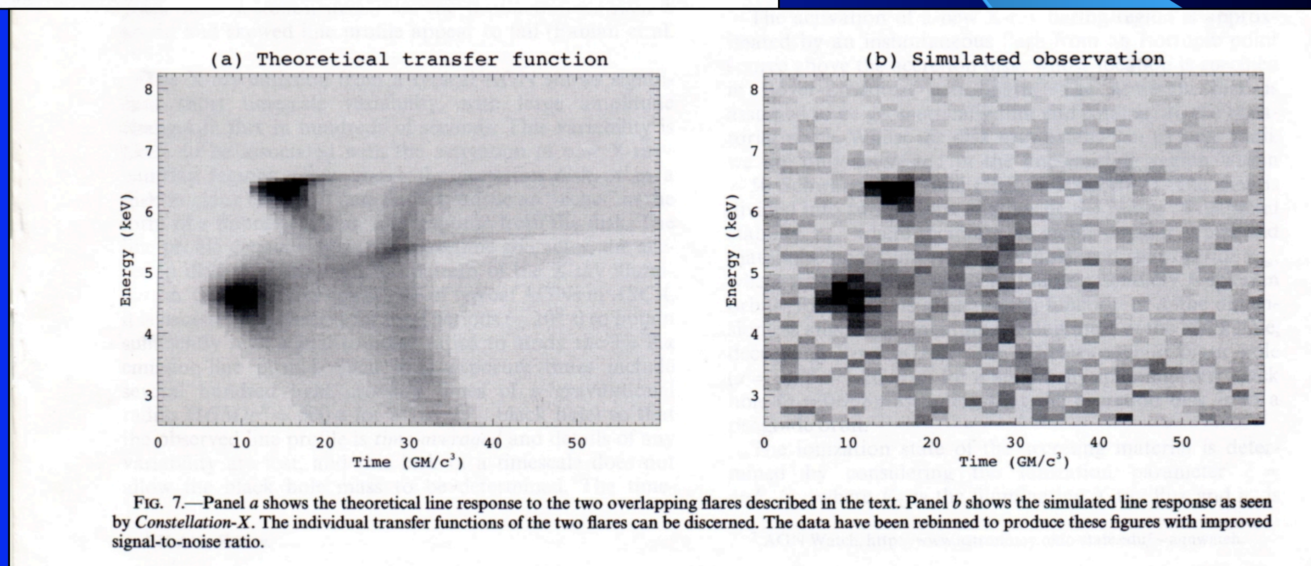
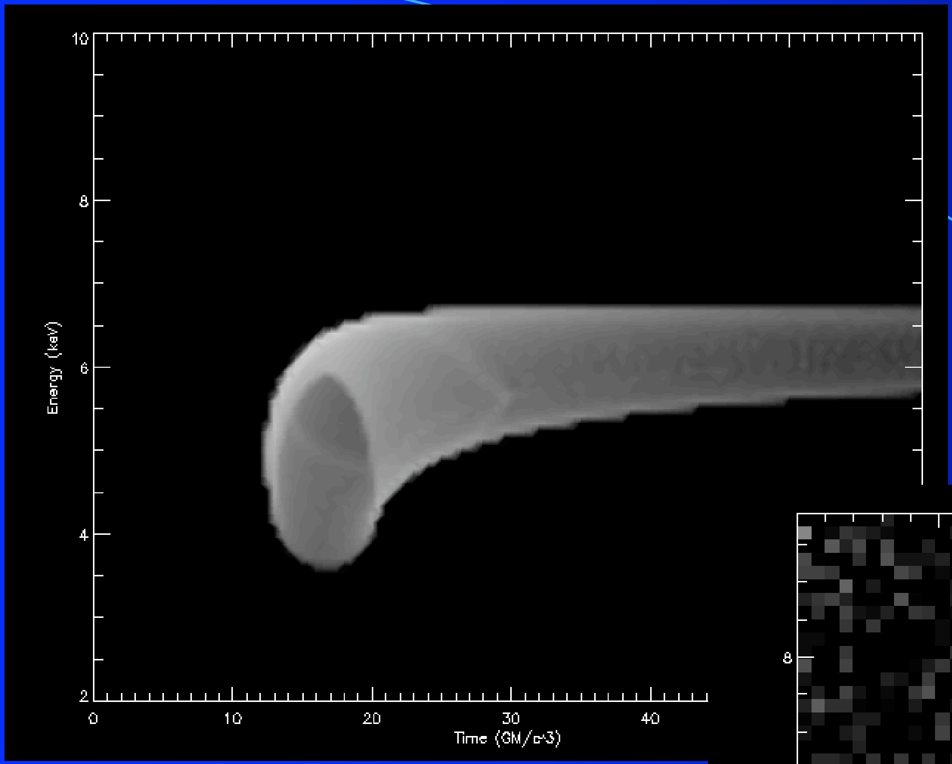
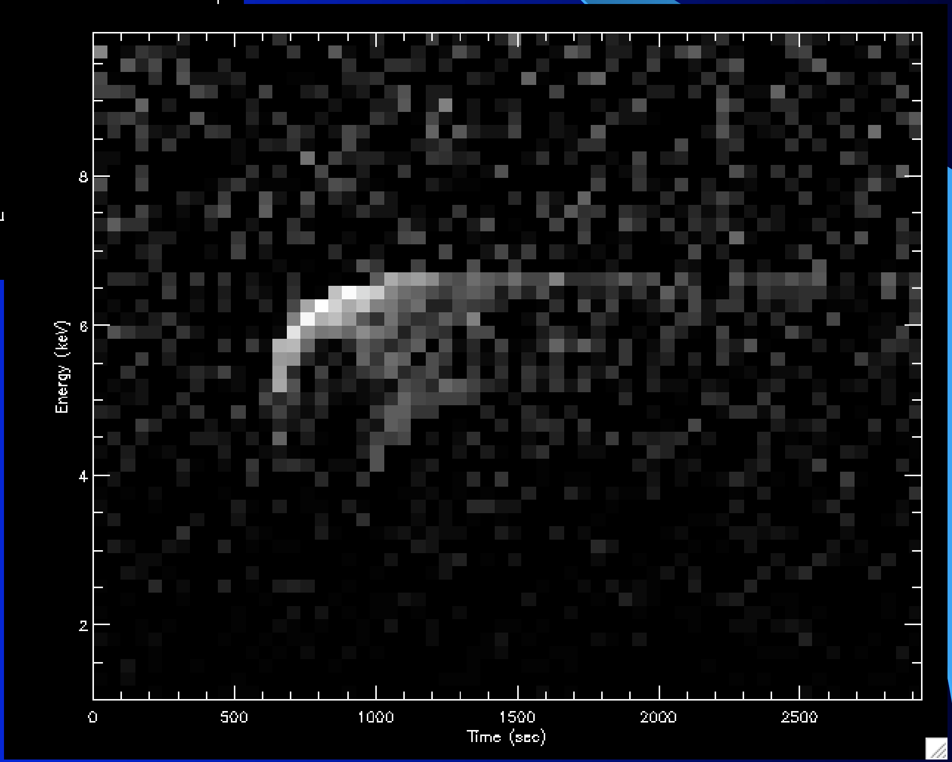
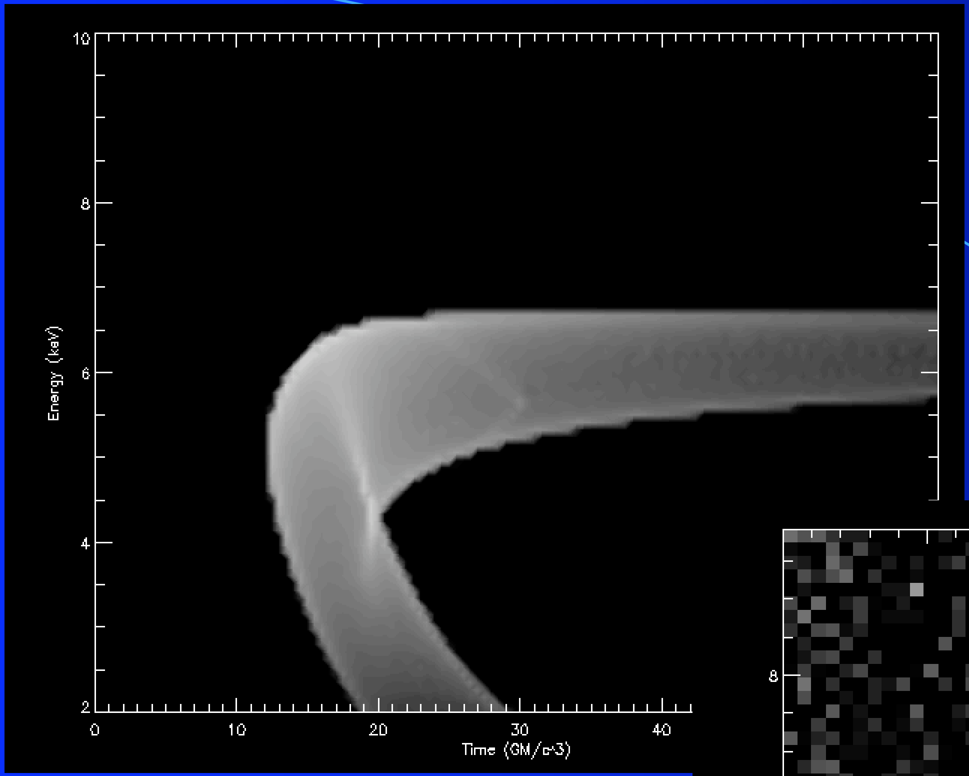


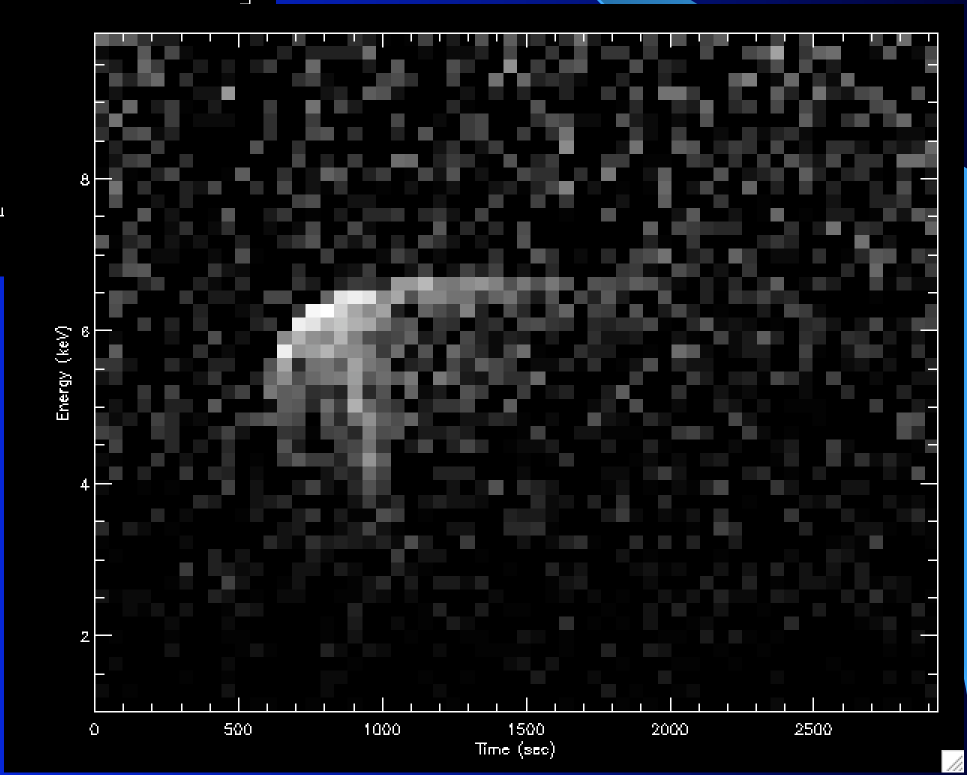
FIG. 7.—Panel *a* shows the theoretical line response to the two overlapping flares described in the text. Panel *b* shows the simulated line response as seen by *Constellation-X*. The individual transfer functions of the two flares can be discerned. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

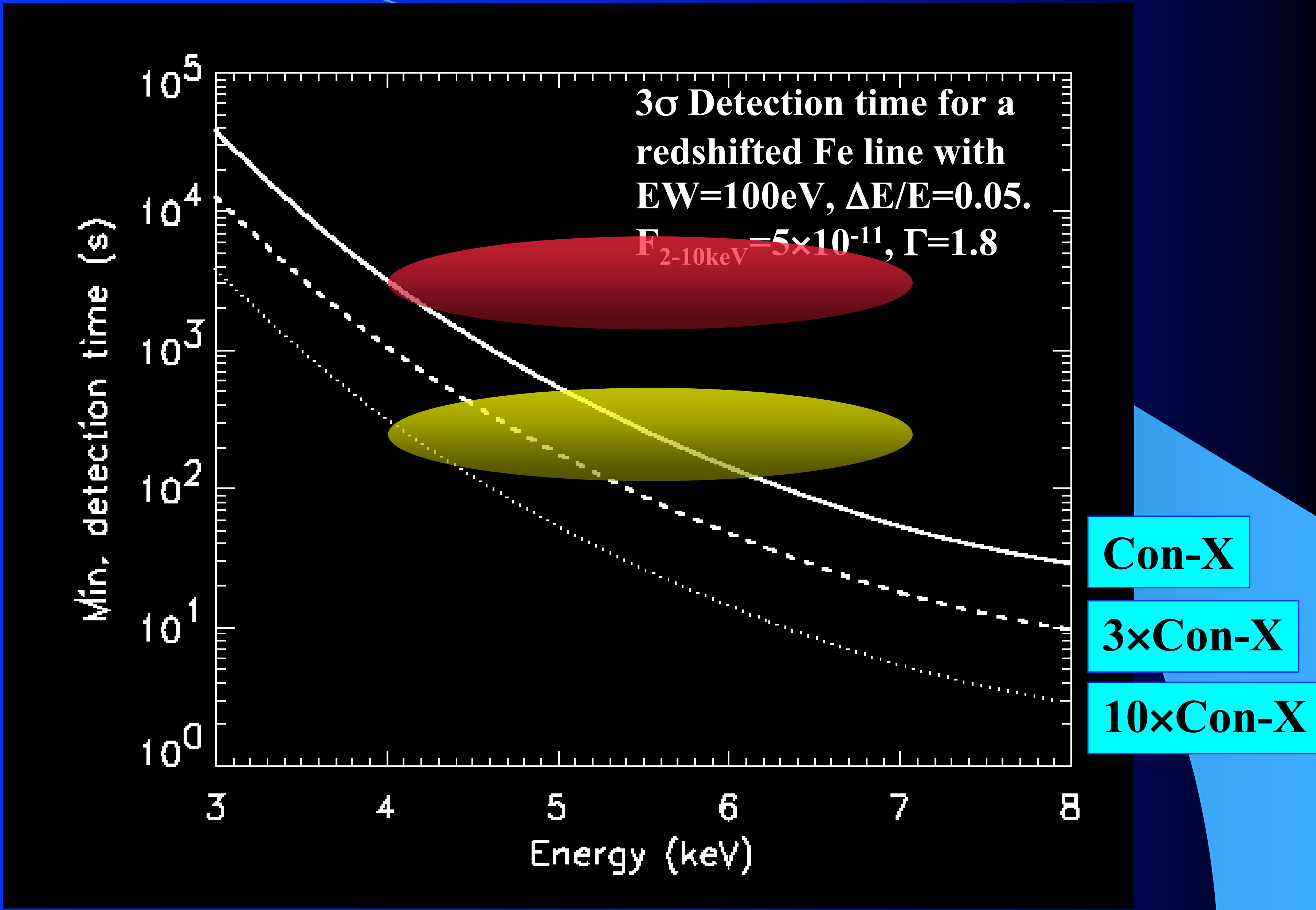
Constellation-X simulations for bright AGN source with $M=10^8 M_{sun}$


Energy (keV)
Time (GM/c^3)


Energy (keV)
Time (sec)

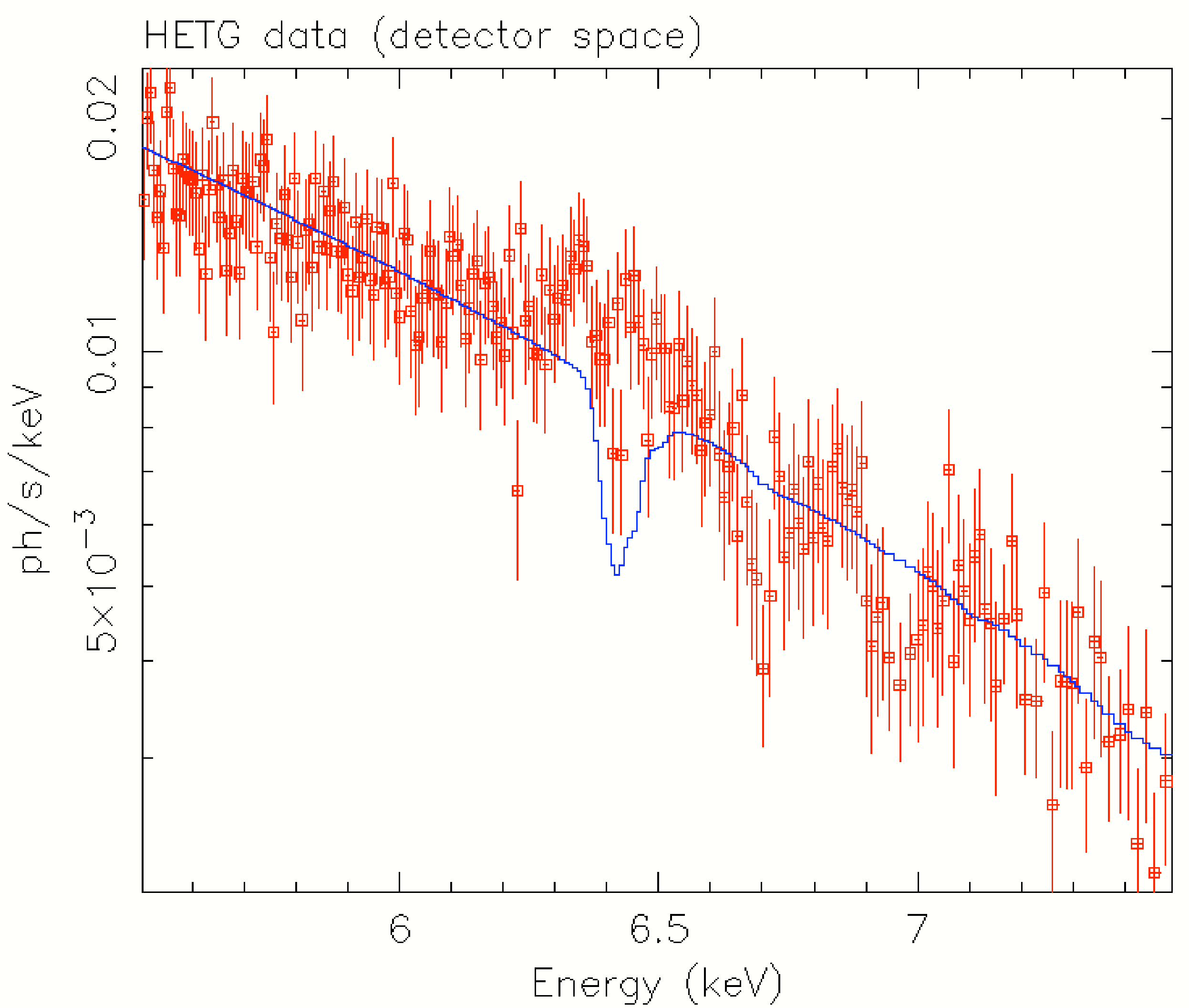

Energy (keV)
Time (GM/c^3)


Energy (keV)
Time (sec)


3σ Detection time for a redshifted Fe line with EW=100eV, ΔE/E=0.05. $F_{2-10keV}=5\times10^{-11}$, Γ=1.8
Min. detection time (s)
Energy (keV)
Con-X
3×Con-X
10×Con-X

The need for high-spectral resolution

- Lesson from XMM… **high-S/N but moderate-resolution spectra have degenerate interpretations**
- Need to be able to unambiguously separate out any “foreground” emission and absorption and study the inner disk
- Astro-E2 will demonstrate whether or not we need high spectral-resolution for disk studies



MCG-6-30-15 512ks Chandra HETG; WA fit to broad line Young et al. (2005)

Observing Strategies II : Large samples of BH sources

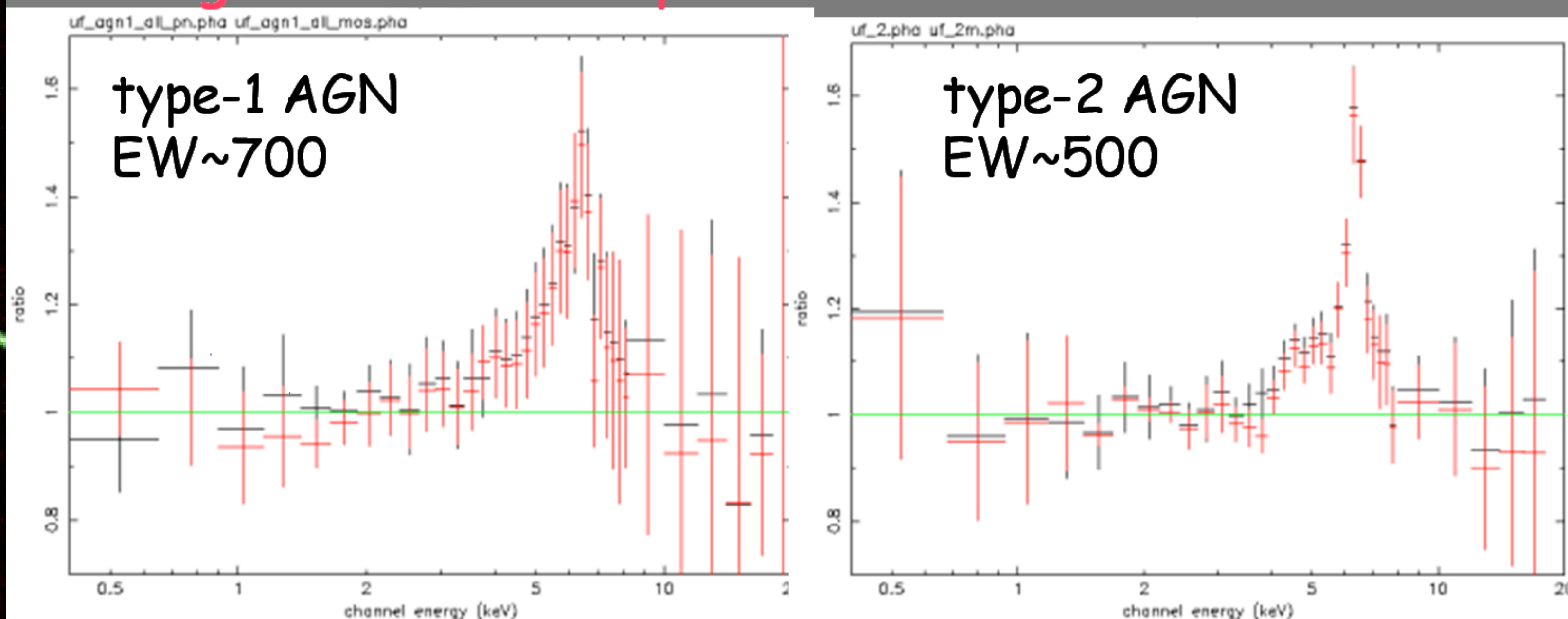
- Use bright AGN to calibrate lower-fidelity spectral probes
  - E.g., time-averaged broad line profiles and continuum spectra as function of mass, spin, accretion rate
- Large samples of AGN, GBHC and ULX/IMBH spectra
  - Demographics of BH mass, spin, accretion rate
  - ONLY way to probe spin in IMBHs and the most massive SMBH (outside of accessible frequency range for all gravitational wave experiments).

Lockman Hole

800 ks XMM-Newton observation

Hasinger

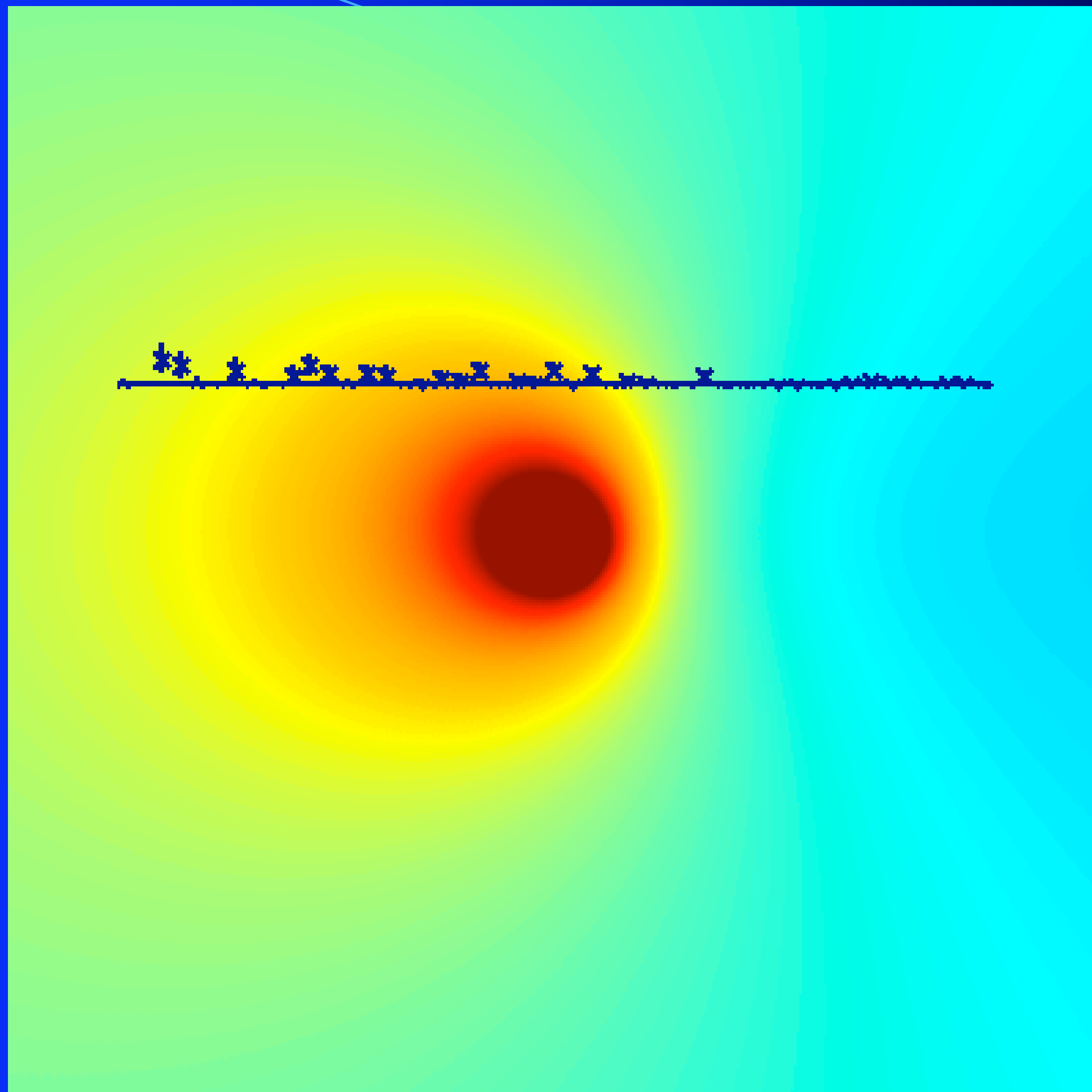
Average rest-frame spectra show relativistic Fe-lines



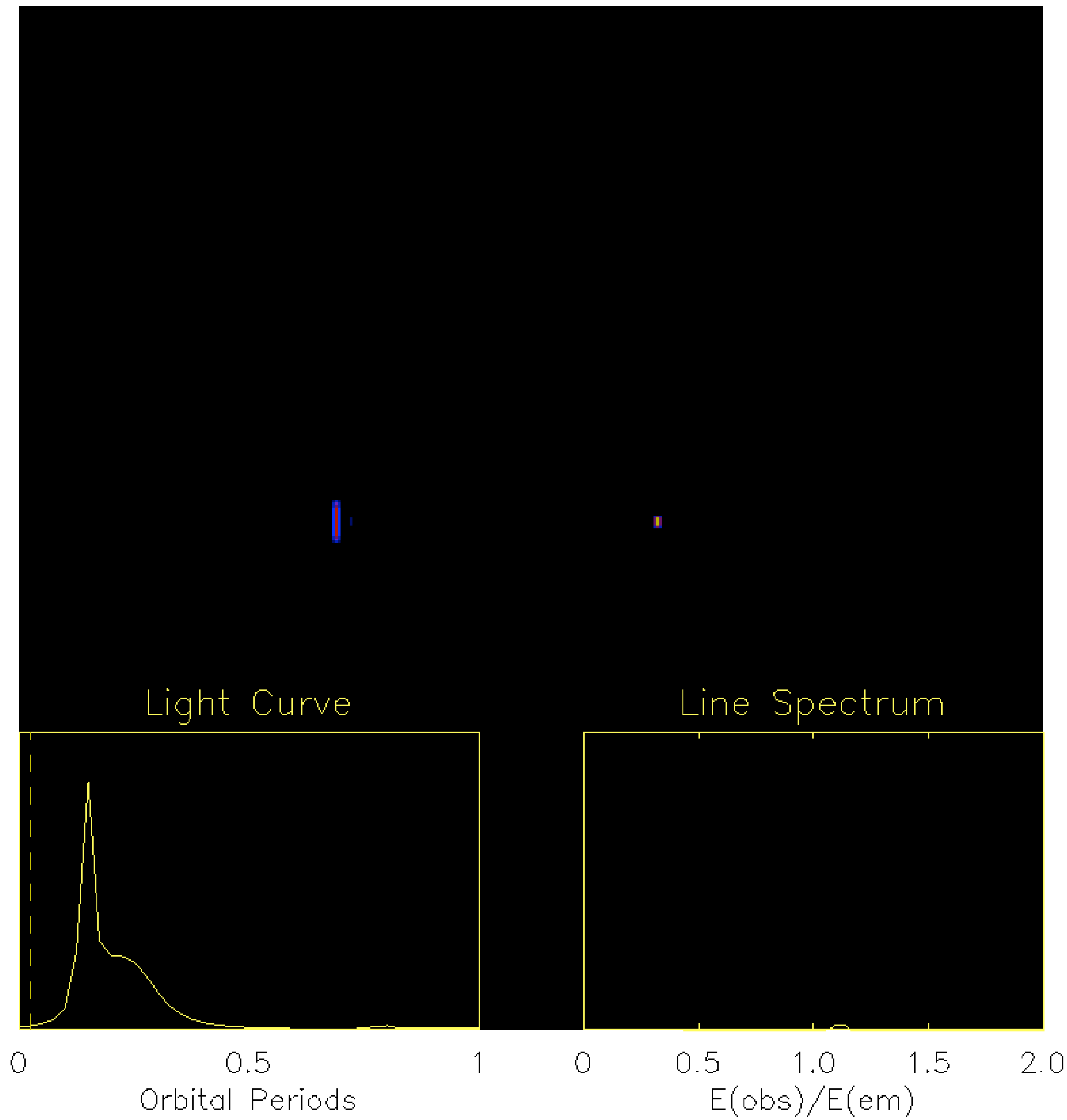
Streblyanskaya et al 2004

Summary and Conclusion

- Strong gravity and spectroscopy
  - Light-crossing timescale broad line variability
  - Dynamical timescale broad line variability
  - Relativistic effects in samples of GBHCs, ULXs and AGN
- Observatory specifications
  - Effective area; A>4m^2@4keV, 2m^2@6keV
  - Spectral resolution; E/ΔE>1000



Courtesy of J.Schnittman



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